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Ionization States and Plasma Structures of Mixed-morphology SNRs Observed with ASCA

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ABSTRACT

We present the results of a systematic study using ASCA of the ionization state for six “mixed-morphology” supernova remnants (MM SNRs): IC 443, W49B, W28, W44, 3C391, and Kes 27. MM SNRs show centrally filled thermal X-ray emission, which contrasts to shell-like radio morphology, a set of characteristics at odds with the standard model of SNR evolution (e.g., the Sedov model). We have therefore studied the evolution of the MM SNRs from the ionization conditions inferred from the X-ray spectra, independent of X-ray morphology. We find highly ionized plasmas approaching ionization equilibrium in all the MM SNRs. The degree of ionization is systematically higher than the plasma usually seen in shell-like SNRs. Radial temperature gradients are also observed in five remnants, with cooler plasma toward the limb. In IC 443 and W49B, we find a plasma structure consistent with shell-like SNRs, suggesting that at least some MM SNRs have experienced similar evolution to shell-like SNRs. In addition to the results above, we have discovered an “overionized” ionization state in W49B, in addition to that previously found in IC 443. Thermal conduction can cause the hot interior plasma to become overionized by reducing the temperature and density gradients, leading to an interior density increase and temperature decrease. Therefore, we suggest that the “center-filled” X-ray morphology develops as the result of thermal conduction, and should arise in all SNRs. This is consistent with the results that MM SNRs are near collisional ionization equilibrium since

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the conduction timescale is roughly similar to the ionization timescale. Hence, we conclude that MM SNRs are those that have evolved over $\sim 10^4$ yr. We call this phase as the “conduction phase.”

Subject headings: conduction — plasmas — radiation mechanisms: thermal — supernova remnants — X-rays: ISM

1. Introduction

The most prominent characteristics of the plasma in a supernova remnant (SNR) are its high electron temperature ($\sim 10^7$ K) and low density ($\leq 1 \text{ cm}^{-3}$). It takes a substantial fraction of the life of a SNR (10^4 – 10^5 yr) for ions in such an optically-thin thermal plasma to reach collisional ionization equilibrium (CIE) with the electrons heated by the shock wave. Such an “underionized” state is often referred to as non-equilibrium ionization (NEI) and has been observed in many SNRs. Thus, investigating the range of ionization states in a SNR provides significant information about its evolution. The objects of the present study are “mixed-morphology” SNRs (MM SNRs) whose formation mechanism is not yet well understood. The properties of MM SNRs have been most succinctly described in Rho & Petre (1998). They have a shell-like radio morphology, and their steep radio spectrum is characteristic of synchrotron radiation from electrons accelerated by the shock wave. In contrast, the X-ray morphology of MM SNRs is centrally peaked, with little or no limb brightening. Unlike the centrally peaked synchrotron radiation from pulsar wind nebulae such as the Crab Nebula, the X-ray emission is thermal, showing line emission from abundant metals such as Mg, Si, S, and Fe. In general, thermal X-rays are thought to arise mainly from the shock-heated and compressed material behind the forward blast wave that would give rise to a shell-like morphology. Thus, the properties of MM SNRs are inconsistent with the initial $\sim 10^4$ yr of the standard model of SNR evolution (i.e., the Sedov model), when the shock front is moving fast enough to heat ambient material to X-ray emitting temperatures. However, MM SNRs represent about 20% of the X-ray detected Galactic SNRs, suggesting that the conditions for creating such remnants are not rare. A large number of them are interacting with molecular clouds and/or H I clouds. For example, OH maser emission at 1720 MHz is detected from seven MM SNRs, a remarkably high fraction (Yusef-Zadeh et al. 2003).

Two scenarios have been invoked to explain the X-ray morphology of MM SNRs. One is that the interior X-ray emission arises from the gas evaporated from shocked clouds (White & Long 1991), implying that MM SNR have evolved under special conditions. The other is that as a SNR evolves, the temperature and density of the hot interior plasma gradually

becomes uniform through thermal conduction, and once the remnant has entered the “shell forming” stage in which the forward shock no longer heats ambient material to X-ray emitting temperatures, it becomes visible as centrally brightened X-ray emission (Cox et al. 1999; Shelton et al. 1999). However, the formation mechanisms of MM SNRs are still controversial. We investigate the ionization degree of the plasma to study the evolution of MM SNR since the ionization state of a remnant can yield an age estimate that is independent of the X-ray morphology.

In this paper, we first describe our selection of targets for analysis of ionization state and plasma structure (section 2). Section 3 presents the analysis and results of individual remnants, the details of which are in Kawasaki (2003). In section 4, we summarize the results of the MM SNRs through comparison with shell-like SNRs. We then discuss possible mechanisms for the creation of the newly-found “overionized” plasma and MM SNRs in general. We conclude that both the plasma structure and ionization conditions can be explained by thermal conduction. We finally present the implications of our findings for the overall picture of SNR evolution.

2. Target Selection

In order to investigate the ionization conditions in MM SNRs, we adopted the following method to supplement global NEI model fits. First, we estimate the electron temperature, kT_e , from the continuum shape of the X-ray spectrum. Next, we measure the intensity ratio of the H-like $K\alpha$ (hereafter $Ly\alpha$) line to the He-like $K\alpha$ (hereafter $He\alpha$) line for the heavy elements, which provides a measure of the degree of ionization as the ionization temperature, kT_z . Comparison between kT_e and kT_z directly gives the ionization state of the SNR from its X-ray spectrum. This method is to produce robust results, then we need to utilize data from an X-ray spectrometer that resolves the $Ly\alpha$ line from the $He\alpha$ line. One such instrument is the Solid-state Imaging Spectrometer (SIS) onboard *ASCA*, which has energy resolution of 5% (FWHM) at 1.5 keV. However, the SIS energy resolution degraded over the course of the mission as a consequence of accumulated radiation damage (Yamashita et al. 1999). Therefore, only data from early *ASCA* observations (from the launch in 1993 through 1994) are suitable for this analysis.

Table 1 tabulates the *ASCA* observations of candidate MM SNRs from Rho & Petre (1998). Among the candidates, MSH 11-54 (G292.2+1.8), their group “F” remnant, is excluded because it is considered to be a reverse-shocked, ejecta-dominated young remnant, showing strong O and Ne lines with a large velocity of $2,000 \text{ km s}^{-1}$ (Goss et al. 1979; Murdin & Clark 1979), and a faint shell in X-rays (Park et al. 2002). For the systematic study of

ionization states, we used only the *ASCA* data. Thus, our criteria of selecting targets in this paper are: (1) MM SNR candidates assigned as A to E in Table 1, and (2) SNRs observed with *ASCA* from 1993 to 1994. There are eight SNRs satisfying these criteria. However, the data from 3C400.2 and MSH 11-61A, observed in 1994, are not suitable for our analysis as mentioned in the notes of table 1. Therefore, we analyzed the following six remnants: IC 443 (G189.1+3.0), W49B (G43.3–0.2), W28 (G6.4–0.1), W44 (G34.7–0.4), 3C391 (G31.9+0.0), and Kes 27 (G327.4+0.4).

3. Data Analysis and Results

For the series of analysis, we extracted all the data from *ASCA* public archive, and screened them using the the NASA/GSFC revision 2 standard data processing criteria. We applied no Residual Dark Distribution (RDD) correction because the early-mission SIS data show few or no radiation damage effects. As most of these remnants are located near the Galactic plane where the Galactic Ridge X-ray emission (GRXE) is not negligible, we used source-free regions of the individual observations for background subtraction. Exceptions to this background subtraction approach were IC 443 and W49B, for which we used blank-sky data: IC 443 is located in the Galactic anti-center region, and the results for W49B are not sensitive to the background used (Hwang, Petre, & Hughes 2000).

When investigating the ionization state, we used a model consisting of a CIE plasma (VMEKAL in XSPEC, Mewe, Gronenschild, & van den Oord (1985); Kaastra (1992); Liedahl, Osterheld, & Goldstein (1995)) and several Gaussian components. A CIE plasma model with metal abundances set to zero represents the continuum shape (i.e., kT_e), while Gaussian components are used to measure the line intensity ratios ($\text{Ly}\alpha/\text{He}\alpha$) of heavy elements (i.e., kT_z). We fixed the Gaussian widths at 10 eV for $\text{He}\alpha$ of Mg, Si, S, and Ar, and 20 eV for $\text{He}\alpha$ of Ca, in order to account for the fact that the $\text{He}\alpha$ lines are triplets. The widths of all other lines were fixed at 0.1 eV, corresponding functionally to monochromatic lines compared with the SIS energy resolution.

For remnants whose angular size is larger than the SIS field of view (FOV), we extracted spectra from a few regions and investigated the plasma structure and ionization state of each. Below, we present the results for individual remnants.

3.1. IC 443

The details of the analysis and results for IC 443 are described in Kawasaki et al. (2002); we briefly summarize the results here. IC 443 has a $\sim 45'$ diameter, and we extracted the spectra from two regions: a central region where the X-ray surface brightness is highest, and a region near the northern rim. Both spectra require two plasma components (1.0 keV and 0.2 keV); the emission of the 0.2 keV plasma is stronger in the region near the shell than the center. In addition, the mean electron densities of the 1.0 keV and 0.2 keV plasmas estimated from the emission measures are 1 cm^{-3} and 4 cm^{-3} respectively. These results can be accounted for by a simple model in which IC 443 has a hot (1.0 keV) interior surrounded by a cool (0.2 keV) and denser shell. In the high-temperature plasma, the ionization temperature from the $\text{Ly}\alpha/\text{He}\alpha$ ratio of S is $\simeq 1.5 \text{ keV}$, significantly higher than the electron temperature of 1.0 keV. Neither an additional, hotter plasma component nor a multi-temperature plasma successfully accounts for this feature, and we conclude that the interior hot plasma of IC 443 is overionized.

We attempted to verify this result using XMM-Newton data. Unfortunately, the observation of IC 443 suffers from high background; the available data do not provide results as statistically accurate as those from *ASCA*.

3.2. W49B

W49B appears centrally brightened in X-rays and shell-like at radio wavelengths, like other MM SNRs. However, this remnant is thought to be ejecta-enriched, and thus relatively young, based on the high (3–5 times as solar) metal abundances (Fujimoto et al. 1995; Hwang, Petre, & Hughes 2000). Since W49B is compact, with a size of only $4' \times 3'$ we used the *Chandra* images with $0.5''$ spatial resolution to ascertain the energy dependence of its morphology. Figure 1 shows the *Chandra* ACIS images in the 1.0–2.12 keV, 2.12–4.10 keV, and 4.25–6.30 keV energy bands. They show that the highest energy image is more centrally concentrated than those in the lower energy bands. The SIS spectrum of the entire remnant in the 0.8–10.0 keV energy band (2CCD mode data) requires at least a two-temperature ($0.24^{+0.04}_{-0.02} \text{ keV}$ and $1.70^{+0.02}_{-0.04} \text{ keV}$) CIE plasma (VAPEC in XSPEC, Smith et al. (2001)) with a large absorption column density of $5.23^{+0.11}_{-0.10} \times 10^{22} \text{ cm}^{-2}$. Furthermore, we had to add four Gaussian components to reproduce unusually strong emission lines of Ar $\text{Ly}\alpha$ and Ca $\text{Ly}\alpha$, whose center energies were fixed at theoretical values of 3.324 keV and 4.105 keV respectively, as well as Cr $\text{He}\alpha$ and Mn $\text{He}\alpha$ lines (Hwang, Petre, & Hughes 2000). The reduction of χ^2 by adding each $\text{Ly}\alpha$ line is more than 10 for 147 d.o.f, and an F-statistic test gives a probability greater than 97% indicating that these lines are real. The resultant $\chi^2/\text{d.o.f.}$ is 233/146 (see

Tab. 2 and Fig. 2).

We therefore evaluated the ionization temperatures of Ar and Ca and compared them to the continuum temperature. In order to achieve a better statistical accuracy, we added the two data sets taken in 1CCD mode (13ksec and 19ksec SIS data) and fitted them simultaneously. We used the spectra in the 2.75–6.0 keV energy band since the contribution of the low-temperature plasma is negligible at these energies. We applied a model consisting of the CIE plasma (VMEKAL) and 9 Gaussian components (He α , Ly α , He β , He γ of Ar, He α , Ly α , He β , He γ of Ca, and He α of Cr) as shown in Figure 3 (*left*). Line center energies of Gaussian components were fixed at the theoretical values except for Ar He α , Ar Ly α , Ca He α , and Ca Ly α . For the W49B plasma with strong emission lines, line blending can be a significant issue when measuring line fluxes with a moderate resolution spectrometer like the SIS. A non-negligible flux from S H-like K β (Ly β) at 3.107 keV can blend with Ar He α (\sim 3.13 keV), as can He β and He γ emission of S at 2.88 keV and 3.02 keV respectively. In these fits, we fixed the S abundance to 3.9 solar as derived from the 0.8–10.0 keV spectrum fitting, instead of adding further Gaussian components. We ignored the Ar Ly β (3.936 keV) flux, which could mildly contaminate (5–10%) the Ca He α . For He β and He γ line blending, we modeled the He γ line with an intensity relative to the He β line fixed at 0.6 (Hwang, Petre, & Hughes 2000). Both Ar and Ca, the Ly α /He α ratio requires an ionization temperature of \sim 2.5 keV; this is higher than the \sim 1.8 keV electron temperature (see Fig. 3 (*right*) for the confidence contours). Adding a third plasma component with higher ($>$ 1.8 keV) temperature can in principle account for the strong H-like lines of Ar and Ca, but it is required to have an implausible combination of small emission measure and extremely large (\gtrsim 100) abundances. Therefore, we suggest that the high-temperature plasma of W49B is “overionized”, similar to IC 443. W49B is thus the second SNR showing overionization.

Our results may be compared with the detailed spectral analysis by Hwang, Petre, & Hughes (2000). They showed the constraints on kT_z for the Ly α /He α of Ar and Ca to be 2.2–2.7 keV. The values are higher than the kT_e of 1.7 keV inferred from the bremsstrahlung continuum. Our results are consistent with theirs, only our interpretation differs.

Taken together, the *Chandra* images and *ASCA* spectra indicate the presence of central hot and outer cool plasmas. We thus suggest that W49B consists of two typical plasma components (a 1.7 keV hot interior and a 0.24 keV cool shell), like that of the Sedov model, though Fujimoto et al. (1995) suggested a possible stratification of ejecta.

The electron densities can be estimated from the emission measures to be

$$n_1 = 2.5 \left(\frac{f_1}{0.64} \right)^{-1/2} \left(\frac{\theta}{2'} \right)^{-3/2} \left(\frac{d}{11.4 \text{ kpc}} \right)^{-1/2} \text{ cm}^{-3}, \quad (1)$$

$$n_2 = 18 \left(\frac{f_2}{0.36} \right)^{-1/2} \left(\frac{\theta}{2'} \right)^{-3/2} \left(\frac{d}{11.4 \text{ kpc}} \right)^{-1/2} \text{ cm}^{-3}, \quad (2)$$

for the high- and low-temperature components respectively, assuming that the two components are in pressure equilibrium and the X-ray emitting volume extends to the radio shell (which we approximate as a spherical region with angular radius $\theta=2'$). Here, f_1 and f_2 ($f_1 + f_2 = 1$) are the filling factors of these components and d is the distance to W49B. This plasma structure, temperature and density distributions, is consistent with the idealization of the Sedov model.

The X-ray emitting masses of the components can also be estimated:

$$M_1 = 49 \left(\frac{f_1}{0.64} \right)^{1/2} \left(\frac{\theta}{2'} \right)^{3/2} \left(\frac{d}{11.4 \text{ kpc}} \right)^{5/2} M_\odot, \quad (3)$$

$$M_2 = 2.0 \times 10^2 \left(\frac{f_2}{0.36} \right)^{1/2} \left(\frac{\theta}{2'} \right)^{3/2} \left(\frac{d}{11.4 \text{ kpc}} \right)^{5/2} M_\odot. \quad (4)$$

The masses of the high- and low-temperature plasmas are much higher than that of any plausible progenitor, even if $d = 8$ kpc which is favored by Moffett & Reynolds (1994). We should note here that the masses are estimated assuming uniform density distributions within the remnant. The *Chandra* images show some clumpy structures as well as the extended components. In fact, the mass of the high-temperature plasma could be $\sim M_\odot$ if the X-rays come only from clumps (Hwang, Petre, & Hughes 2000). However, the extent of the 1.00–2.12 keV *Chandra* image (see Fig. 1) indicates that the mass of the low-temperature component is much higher than the ejecta mass. Coupled with the surprisingly close proximity of the plasma to ionization equilibrium (in stark contrast to ejecta-dominated remnants (e.g., G292.0+1.8 – (Hughes & Singh 1994)), the high mass leads us to suggest that W49B is not a young, ejecta-dominated, but an evolved MM SNR.

The mass and ionization state of W49B are reasonably explained if the plasma is dominated by the shocked ambient medium, but its large abundances and high temperature (up to $\simeq 1.7$ keV) strongly suggests the presence of ejecta. Overabundances might be explained if W49B exploded in the massive ($\sim 10^2 M_\odot$) circumstellar cloud with large amount of heavy elements seeded by previous SNRs. The X-ray measured absorption column density is $5.23^{+0.11}_{-0.10} \times 10^{22} \text{ cm}^{-2}$, significantly higher than the Galactic column density of $4.4 \times 10^{22} \text{ cm}^{-2}$ measured in this direction using the 21cm and CO observations (Dickey & Lockman 1990; Stark et al. 1985). The X-ray absorption is mainly due to heavy elements, not hydrogen. Thus, this high column density might indicate that W49B is embedded in an unusually metal rich environment. More detailed investigation using higher resolution spectrometers will be needed to resolve this question, and it is clearly outside the scope of this work.

3.3. W44

We show in Figure 4 the smoothed images of W44 in the 0.7–1.5 keV and 1.5–4.0 keV bands using the Gas Imaging Spectrometer (GIS). The soft (0.7–1.5 keV) image has a larger angular extent than the hard (1.5–4.0 keV) one, suggesting spectral variations due to a temperature gradient. Furthermore, clear differences are found in fits to spectra from the central and northern regions shown in Figure 4. The temperature of the central region, $0.84^{+0.02}_{-0.05}$ keV, is higher than that of the northern, $0.64^{+0.04}_{-0.05}$ keV. This is consistent with the fact that the hard band image is more centrally concentrated. We also found higher abundances of Mg and Si, significant at the 90% confidence level, in the central region: e.g., the abundance of Si is $1.18^{+0.24}_{-0.12}$ in the center while in the north it is $0.50^{+0.10}_{-0.04}$. This enhancement could be due to residual ejecta, as first detected in the Cygnus Loop (Miyata et al. 1998). The best fit ionization timescale is $>10^{12}$ s cm^{-3} for both regions. Details are tabulated in Table 3. The *Chandra* data also show the remnant’s hot and metal-rich projected center with bright knots (Shelton, Kuntz, & Petre 2004a). Note that the SIS data exhibited a slight energy shift, which are also shown in the *Chandra* data (Shelton, Kuntz, & Petre 2004a).

The ionization state of the W44 plasma was investigated using line intensity ratios. In this fit, we used the 1.6–6.0 keV band spectra (see Fig. 5(a)). An interstellar absorption value was fixed to $8.9 \times 10^{21} \text{ cm}^{-2}$, which was obtained from the NEI fits. The ionization temperature of Si in the central region, obtained from the fitted $\text{Ly}\alpha/\text{He}\alpha$ ratio, is $\simeq 0.7$ keV. This is consistent with the electron temperature of $\simeq 0.8$ keV as shown in Figure 5(b), as well as with the NEI model fitting. The inferred kT_z of Si in the north region is ~ 0.8 keV, with a large (0.5–1.5 keV) statistical uncertainty.

3.4. W28

The X-ray morphology of W28 is basically center-filled, but is more complex than the other MM SNRs. It has ear-like segments of limb-brightened shell in the northeast and northwest (Rho & Borkowski 2002). In addition, we found with the *ASCA* GIS that the emission from the northeastern part is strong in the soft band (0.5–1.5 keV) but not in the hard (1.5–4 keV). This is also indicated by Figures 6 and 8 in Rho & Borkowski (2002).

We extracted the spectra from the central area, named “center” (a rectangular region with $8' \times 7'$ centered at R.A.= $18^{\text{h}}00^{\text{m}}26^{\text{s}}$, Dec.= $-23^{\circ}26'49''$) and the eastern area, named “east” (an elliptical region with $4.8' \times 4.1'$ centered at R.A.= $18^{\text{h}}00^{\text{m}}36^{\text{s}}$, Dec.= $-23^{\circ}23'45''$). The spectrum was well fitted by the two NEI (VNEI) components with temperatures of

0.6 keV and 1.4 keV in each region (see Tab. 4). The ionization timescale of both components are around 10^{12} s cm^{-3} . The abundances of Ne, Mg, Si, S, which were linked together for the two plasmas, are fitted with $\lesssim 1$ times solar values (Anders & Grevesse 1989). The column density is 5.1×10^{21} cm^{-2} and 5.4×10^{21} cm^{-2} for the center and the east, respectively. We found a larger fraction of high-temperature plasma in the center region (the emission measure ratio is $0.51_{-0.19}^{+0.25}$) than that in the east (the ratio is $0.31_{-0.04}^{+0.06}$). In contrast, the northeastern shell consists of only a low-temperature plasma ($kT_e=0.56$ keV, $n_e t=1.7 \times 10^{13}$ s cm^{-3}) (Rho & Borkowski 2002). Therefore, we suggest that low-temperature component becomes dominant toward the northeastern rim of the remnant where dense molecular clouds are present. These results are consistent with those of IC 443 (Kawasaki et al. 2002), implying that the plasma structure of a hot interior and a cool exterior is present in W28. On the other hand, the southwestern shell region shows hard X-ray emission. Rho & Borkowski (2002) showed that the spectrum in this region can be fitted with a temperature of 1.5 keV and $n_e t=1.5 \times 10^{11}$ s cm^{-3} . This implies that the plasma structure of W28 is more complex than allowed by the above simple model.

The ionization state of the high-temperature plasma was examined using line intensity ratios. We used the spectra in the 1.65–6.0 keV energy band although they include contamination by the low-temperature plasma (see Fig. 5(c)). We thus modeled the column density and low-temperature plasma with all parameters fixed to the values estimated from the component fits. The ionization temperature of Si in the east region, from the fitted $\text{Ly}\alpha/\text{He}\alpha$ ratio, is close to the fitted electron temperature as shown in Figure 5(d), although the poor statistics do not constrain the temperatures well. The inferred kT_e and kT_z of Si in the central region are $1.19_{-0.18}^{+0.22}$ keV and >1.06 keV, respectively. These results indicate that the high-temperature plasma is near CIE in each region. Hence, our direct estimate of the ionization state suggests that the plasma in W28 has reached ionization equilibrium, consistent with the results of the NEI fits.

3.5. 3C391

3C391 shows an elliptical X-ray morphology, with a size of $7' \times 5'$, and major axis oriented from northwest to southeast. Chen & Slane (2001) found that the *ASCA* hard band (2.6–10 keV) image shows stronger emission in the northwest, in anti-correlation with the soft band (0.5–2.6 keV) image. This difference is due to the larger column density in the northwest. The variation of the column density across the remnant is in agreement with the presence of a molecular cloud to the northwest. No temperature gradient has been detected across the remnant, a result confirmed by *Chandra* (Chen et al. 2004).

We extracted the spectrum of the entire remnant, in the energy band 0.8–5.0 keV. We first applied a single NEI model, and obtained an electron temperature and ionization timescale $0.53^{+0.4}_{-0.3}$ keV and $2.5 (>0.9) \times 10^{12}$ s cm $^{-3}$. These suggest that the plasma has reached ionization equilibrium (see Tab. 5). We then measured the ionization degree of the plasma using line intensity ratios (see Fig. 5(e)). Since the spectrum shows prominent emission from He α lines of Mg, Si, and S with good energy resolution, we left their center energies free; those of the others were fixed to the theoretical values. Figure 5(f) shows confidence contours of kT_z to kT_e for Mg and Si, and indicates that the ionization temperature is comparable with the electron temperature. Thus, both our direct estimate and NEI model fitting suggest that the plasma in 3C 391 is near ionization equilibrium.

3.6. Kes 27

Kes 27 shows diffuse, thermal X-ray emission with several unresolved point-like sources (Seward, Kearns, & Rhode 1996). Using *ASCA* data, Enoguchi et al. (2002) found a temperature gradient from the rim ($0.59^{+0.04}_{-0.06}$ keV) to the interior (0.84 ± 0.08 keV). This temperature variation is similar to that in W44 (see §3.3).

The 0.8–6.0 keV SIS spectrum of the entire remnant is well fitted by a single NEI model (see Tab. 6). The inferred electron temperature, column density, and ionization timescale are 0.9 ± 0.1 keV, $2.2 \pm 0.1 \times 10^{22}$ cm $^{-2}$, and $> 3 \times 10^{11}$ s cm $^{-3}$, respectively. We measured the ionization state of Kes 27 using the line intensity ratios of Si and S, as shown in Figure 5(g) and (h). The center energies of all the lines are fixed to the theoretical values for a 0.9 keV CIE plasma. The inferred Ly α /He α ratio for Si indicates that the ionization temperature of Si is close to the electron temperature. However, that of S may require an ionization temperature larger than the continuum temperature, suggestive of an overionized plasma, although this statement is significant at a confidence level of $< 90\%$. The results indicate that the plasma in Kes 27 is basically in ionization equilibrium, but the strong S Ly α emission suggests possible overionization.

4. Discussion

4.1. Comparison with Shell-like SNRs

4.1.1. Plasma Structure

We first summarize in Table 7 the spatial distributions of electron temperature and density for the six MM SNRs. IC 443 and W49B show clear evidence of temperature and density gradients; they obviously indicate that these SNRs have a hot interior surrounded by a dense, cooler exterior plasma, qualitatively consistent with that of a standard shell-like SNR. We note that these temperature and density gradients are not as large as those predicted by the Sedov solution. Additionally, W44, W28, and Kes 27, show temperature gradients; they have higher electron temperature towards the center where the X-ray surface brightness is highest than towards the edge. A similar temperature gradient has been detected from an ISM dominated shell-like SNR, the Cygnus Loop (Miyata et al. 1994, 1998), as tabulated in Table 7. These results suggest that MM SNRs have experienced similar evolution to shell-like SNRs. 3C391 (Chen & Slane 2001; Chen et al. 2004) is the only SNR with no detectable temperature or density gradient of the six studied here.

4.1.2. Ionization States

We summarize in Table 8 the electron and the ionization temperatures of the MM SNRs we have analyzed. Two of them, IC 443 and W49B, show significantly higher ionization temperatures than electron temperatures, suggesting the plasma is overionized. For the other remnants, the two temperatures are comparable, suggesting that the plasma has almost reached CIE. This is supported by the long ionization timescales obtained by the NEI model fits.

For comparison, we tabulate in Table 9 the electron temperature (kT_e), ionization timescale ($n_e t$), and ionization temperature (kT_z) of prominent shell-like SNRs. Cassiopeia A (Cas A), Kepler’s SNR, and Tycho’s SNR exemplify the young (~ 500 yr) SNRs, and the others are examples of middle-aged ($\gtrsim 1000$ yr) SNRs. We inferred kT_z of each SNR by the following method: from kT_e and $n_e t$, the emissivities of $\text{He}\alpha$ and $\text{Ly}\alpha$ lines for heavy elements are calculated using an NEI plasma code (Masai 1984, 1994); their ratio, $\text{Ly}\alpha/\text{He}\alpha$, yields the ionization temperature kT_z . We estimated the $\text{Ly}\alpha/\text{He}\alpha$ ratios for Ne, Mg, Si, and S using this method; the inferred kT_z values are consistent with one another within $\simeq 0.2$ keV. The validity of this estimate is checked with the Cas A spectrum as follows. We fitted the SIS spectrum of Cas A with two NEI (VNEI) models; the measured kT_e and $\log(n_e t)$ of the

high-temperature plasma are 3.02 keV and 10.83, respectively, from which we estimate kT_z of S as $1.07^{+0.02}_{-0.04}$ keV. On the other hand, we derived the kT_z of S for the high-temperature plasma to be 0.94 ± 0.07 keV, from the fitted intensity ratio of Ly α to He α (Ly α /He α) as we did for MM SNRs. In this fit, the low-temperature plasma was modeled as another plasma component, in the same way as for W28. The ionization temperatures derived with the two methods are consistent within 0.1–0.2 keV. Thus, we confirmed that the values tabulated in Table 9 properly represent kT_z of these shell-like SNRs, and can be compared with those for MM SNRs.

Figure 6 shows the correlation between kT_e and kT_z for both the MM and shell-like SNRs. We can see a systematic difference between the two types of SNRs. All MM SNRs show $kT_z \gtrsim kT_e$, which means that the plasma has reached CIE or a state of overionization. On the other hand, all of the shell-like SNRs show $kT_z < kT_e$, indicating underionized plasma conditions. These results strongly suggest that MM SNRs are systematically more ionized than shell-like SNRs.

4.2. Formation Mechanisms of the Overionized Plasma

We also found that Ly α line emission from IC 443 and W49B is unusually strong compared with He α , indicating that the interior plasma in these remnants is overionized. In the low density plasma found in SNRs, we are accustomed to encountering underionized plasma, like that detected in shell-like SNRs, because the ionization timescale is typically long compared with the time since the bulk of the gas was shock-heated. Nevertheless, conditions can exist in which such SNR plasmas can become overionized.

We consider two possible causes for overionization: photoionization, and rapid gas cooling compared with recombination. For photoionization, a low-density SNR plasma itself does not produce sufficient radiation to photoionize heavy elements, and there is no strong X-ray source in any of these remnants (see Fig 1 for W49B, and Kawasaki et al. (2002) for IC 443.) On the other hand, there are three possible cooling mechanisms in a gas: radiation, expansion, and thermal conduction. Kawasaki et al. (2002) compared these timescales with that of recombination, and showed that in IC 443 thermal conduction could drive the plasma into an overionized state. A similar comparison can be carried out for W49B. The conduction timescale, $9 \times 10^{10} (n_1/2.5 \text{ cm}^{-3}) (l_T/10^{19} \text{ cm})^2 (kT_1/1.8 \text{ keV})^{-5/2} (\ln \Lambda/32.2) \text{ sec}$, is shorter than the recombination timescale of $4 \times 10^{11} (n_1/2.5 \text{ cm}^{-3}) \text{ sec}$, while the radiative cooling timescale is $3 \times 10^{14} (kT_1/1.8 \text{ keV}) (\theta_1/1.7')^{3/2} (d/11.4 \text{ kpc})^{1/2} \text{ sec}$. Here, n_1 , θ_1 , and kT_1 are the number density, the radius in arcminutes, and the temperature of the inner plasma of W49B, respectively, and l_T , and $\ln \Lambda$ are the scale length of the temperature gradi-

ent and Coulomb logarithm. We note that the cooling timescale via expansion is 12.5 times the remnant’s age (Masai 1994), meaning that the remnant has not been cooled enough at present time. This indicates that thermal conduction is the dominant process producing the overionized plasma in W49B as well as in IC 443.

The presence of a magnetic field will reduce the heat flux in principle, because diffusion perpendicular to the field direction is suppressed. The magnetic field reduces the heat flux by a factor of $\sim \langle \cos^2 \theta \rangle = 1/3$ if it is tangled, but the conduction timescale still remains comparable to the recombination timescale. Although detailed information about the magnetic field in W49B is unavailable, we conclude from the above argument that it is possible for the gas to be overionized due to thermal conduction. The fact that we have not detected in any SNR as large a temperature distribution as predicted by the Sedov solution further suggests that thermal conduction is operating in many remnants.

The process of thermal conduction should arise in all SNRs, as Cox et al. (1999); Shelton et al. (1999) have introduced and discussed thermal conduction over the lifetime of an SNR. Therefore, we investigated the differences between overionized SNRs and the other MM SNRs by comparing the ionization states (i.e., kT_z/kT_e) plotted against the ratios between the conduction timescale and the recombination timescale ($t_{\text{cond}}/t_{\text{recomb}}$) for the six remnants we have analyzed. In the calculation of the conduction timescale, we ignored the effect of the magnetic field. The ratio of the timescales has strong dependence on the density, temperature gradient, and electron temperature as $t_{\text{cond}}/t_{\text{recomb}} \propto n^2 l_T^2 (kT_e)^{-5/2}$. This figure suggests that conduction in W44 and 3C391 is not strong enough to produce overionization, consistent with the observations. On the other hand, our estimates suggest Kes 27 and W28 might be overionized, even though our analysis reveals no clear evidence. Two possibilities are considered for the discrepancy: one is that we could not detect the evidence because of the poor statistics as described in §3.6 for Kes 27; the other is that the magnetic field or some other process reduces the heat flux. We also compared the ionization state to the temperature gradient within the remnants because the temperature gradient strongly affects the thermal conduction as described above. In Figure 7 (*right*) we compare the ionization state against the temperature ratio between the exterior and the interior (kT_e (exterior)/ kT_e (interior)) for the six MM SNRs. This figure indicates that overionized SNRs have a larger temperature gradient than the other MM SNRs (Note, however that temperatures of the interior and the exterior were not estimated in the same way for the six remnants.) We also suggest that MM SNRs with no overionization, such as W44 and 3C391, can be those which conduction has taken further from an overionized state since thermal conduction gradually reduces the temperature gradient within the remnant.

4.3. SNR Evolution and Formation of MM SNR

As we described in §4.2, thermal conduction arises in an SNR, and it equilibrates the temperatures while keeping the pressure balanced. It suggests that the hot interior plasma gradually becomes denser. Therefore, we propose the following unified scenario for SNR evolution. We present in Figure 8 a schematic view on the evolution of the ionization state in a remnant. Numerical simulations by Shelton (1998, 1999) also predict both the center-filled X-ray morphology and overionization as a result of the SNR evolution.

In a young remnant at an early adiabatic or Sedov phase, the strong front shock heats the ambient ISM to high temperatures and bright X-rays appear along the outer rim. The hot gas within the post-shock interior is rarefied compared to the shell regions, and hence, the “shell-like” morphology in X-rays is formed. The observed plasma is mainly from recently shocked regions where ions are being ionized to higher ionization states by electrons on the timescale of $n_e t \sim 10^{12} \text{ s cm}^{-3}$. Therefore, an underionized plasma is detected (*phase-1* in Figure 8).

As the remnant evolves, the hot interior plasma gradually approaches a uniform temperature via thermal conduction, while maintaining the pressure equilibrium. Thus, the interior also becomes denser, resulting in an enhancement of the X-ray emission from the central region. In contrast, the shock speed decreases and the X-ray emission from the shock-heated shell becomes too soft to pass through the ISM. These lead the X-ray morphology to change from “shell-like” to “center-filled” on the conduction timescale, which is the formation mechanism of MM SNR. Since the conduction timescale is roughly comparable to the ionization timescale, $t_{\text{cond}} \sim t_{\text{recomb}} \simeq 10^{12} \text{ s cm}^{-3}$, ionization states of the remnants reach nearly an ionization equilibrium as derived from our analysis of MM SNRs. This phase can be termed the “conduction phase” since thermal conduction plays an important role to the SNR plasma.

If the conduction timescale is shorter than the ionization timescale, the interior plasma could become “overionized” over a certain interval, as observed in IC 443 and W49B (*phase-2* in Figure 8). It is uncertain how long this interval lasts, but the plasma will eventually reach another ionization equilibrium because conduction becomes insufficient as the interior plasma cools and the temperature gradient disappears (*phase-3* in Figure 8). When the conduction becomes fully efficient, no temperature gradient remains in the remnant, as observed in 3C391. Figure 7 (*right*) may indicate the evolution from the overionized SNR (*phase-2*) to the fully conducted SNR (*phase-3*).

This interpretation is supported by the X-ray morphological analysis of SNRs in the Magellanic Clouds that “centrally brightened” SNRs are larger in size than “shell-type” SNRs

(Williams et al. 1999), and by G65.3+5.7, the remnant newly identified to be in transition from shell-like to MM (Shelton, Kuntz, & Petre 2004b). It is controversial to include W49B to the MM SNR type since it has been considered to be ejecta-dominated plasma. However, from the point of view of ionization, thermal conduction plays an important role in W49B, whether it is ejecta or not, and it supports the above interpretation.

5. Conclusions

We have discovered the following results from the systematic analysis of the six MM SNRs.

1. Hot interior and cool outer plasma components are detected in five MM remnants. A higher density is found in the cool exterior than that in the hot interior from both IC 443 and W49B. These results suggest a plasma structure consisting of a central hot region surrounded by a cooler, denser shell, similar to the expected structure of a shell-like SNR.
2. The X-ray emitting gas in IC 443 and W49B is “overionized;” the gas in the other MM SNRs are found to be near ionization equilibrium. As a consequence, the degree of ionization in MM SNRs is systematically higher than in shell-like SNRs.

The first result indicates that MM SNRs have experienced a similar evolution to shell-like SNRs, and the second result indicates that MM SNRs are more evolved than shell-like SNRs. We suggest that thermal conduction plays an important role in producing the overionized interior plasma in IC 443 and W49B. It also acts to diminish the temperature and density gradients within all remnants, leading naturally to a “center-filled” X-ray morphology. Hence, we conclude that MM SNRs are those which have evolved over a conduction timescale of $\sim 10^{11-12}$ sec with thermal conduction active within the remnants. It is also suggested from the fact that plasmas of MM SNRs are nearly in CIE, with the estimated ionization timescale of $\sim 10^{12}$ sec. We propose to call this phase the “conduction phase” since thermal conduction drastically changes the plasma structure of an SNR in this phase far from that in the Sedov phase. By introducing thermal conduction, we showed that MM SNRs are not special SNRs but those in a certain stage of an SNR evolution. This leads to the construction of a unified model of SNR evolution.

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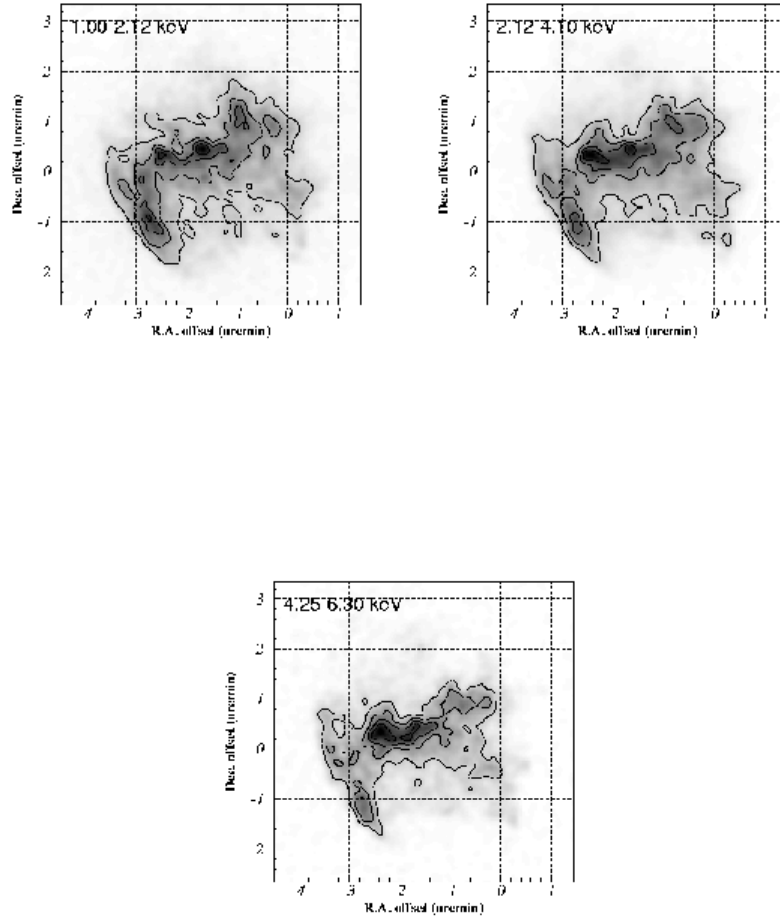


Fig. 1.— *Chandra* ACIS images of W49B in (*left*) 1.00–2.12 keV, (*middle*) 2.12–4.10 keV, and (*right*) 4.25–6.30 keV bands. Grayscales are linear and the contour levels in each figure are 20%, 40%, 60%, and 80% of the peak surface brightness. Offset center in each figure is R.A.=19^h11^m1^s35, Dec.=9°06′7.64″(J2000). All images are derived from *Chandra* Supernova Remnant Catalog Web page (<http://hea-www.harvard.edu/ChandraSNR/>).

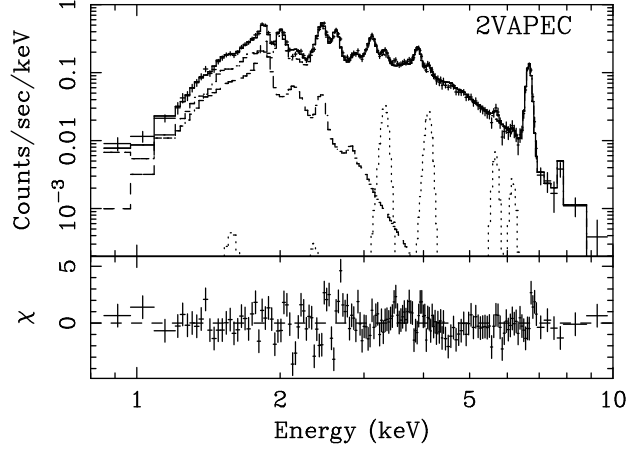


Fig. 2.— ASCA SIS spectra of the entire region of W49B with the best-fit 2 CIE plasma and Gaussians model. Dashed, dash-dotted, and dotted lines represent the low-T plasma, high-T plasma, and additional Gaussian components respectively. The lower panels show the residuals of the fits.

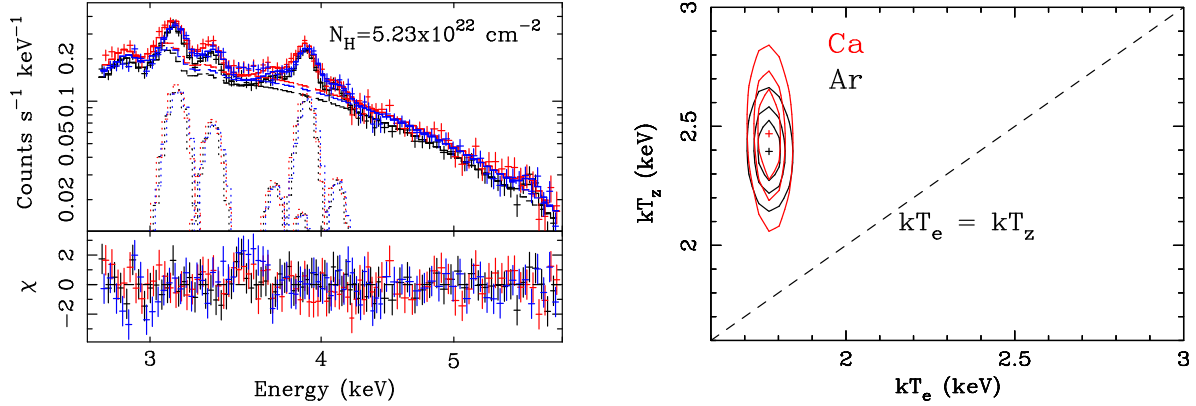


Fig. 3.— *left*: ASCA SIS spectra of W49B in 2.75–6.0 keV energy band with the best-fit model of VMEKAL (dashed) and 9 Gaussian lines (dotted). The data in 2CCD mode are plotted in black, and those in 1CCD mode are in red and blue. The column density is fixed to $N_H = 5.23 \times 10^{22} \text{ cm}^{-2}$. The minimum value of $\chi^2/\text{d.o.f.}$ is 210/235. The lower panel shows the fit residuals. There are residuals at ~ 3.5 keV, which can be identified as a He-like $K\alpha$ line of potassium. *right*: Confidence contours of ratio of the ionization temperature (kT_z) to the electron temperature (kT_e) for Ar (black) and Ca (red) with a fixed column density of $5.23 \times 10^{22} \text{ cm}^{-2}$. The confidence levels are 99%, 90% and 67%. The dashed line represents CIE.

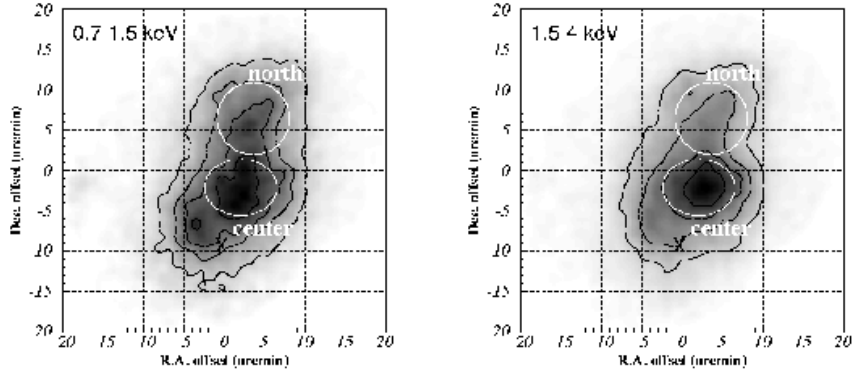


Fig. 4.— Smoothed GIS images of W44 in the 0.7–1.5 keV and (*left*) 1.5–4.0 keV (*right*) bands. Grayscales are in linear scale and contour levels in each figure are 20%, 40%, 60%, and 80% of the peak surface brightness. Spectral extraction regions named “center” and “north” are shown in white ellipse and circle, respectively.

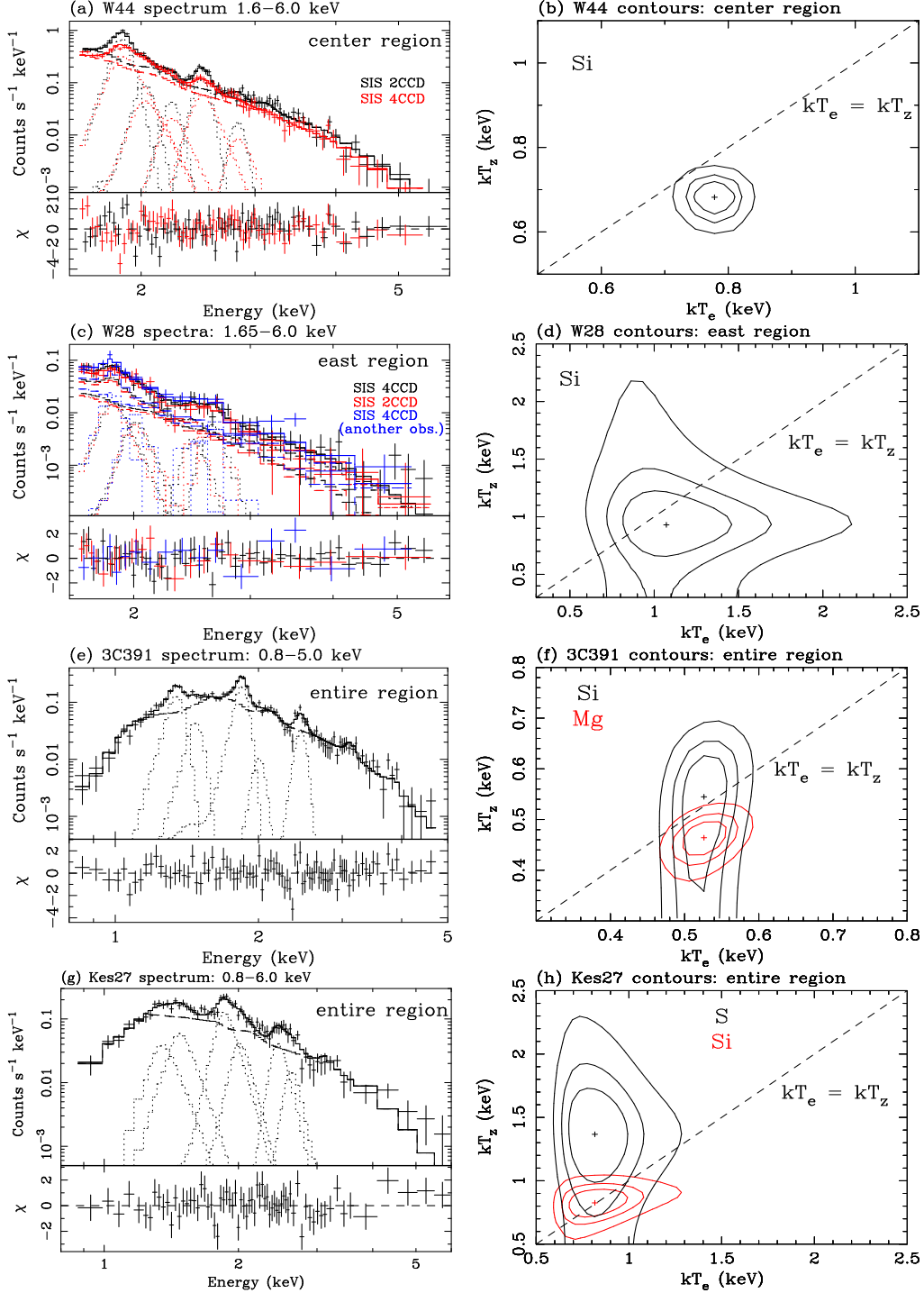


Fig. 5.— X-ray spectra and confidence contours of the ratio of the ionization temperature (kT_z) to the electron temperature (kT_e) for W44, W28, 3C391, and Kes 27. In each spectrum, the dashed line (and dash-dotted line for W28) shows the continuum component while dotted lines represent line features. The lower panel shows the residuals of the fit. In each contours, confidence levels are 99%, 90% and 67%. The dashed line represents $kT_e = kT_z$, meaning that the plasma is at the CIE state.

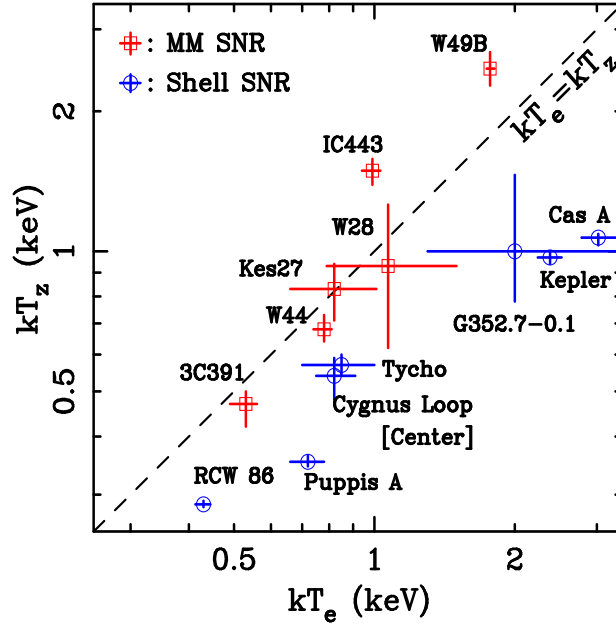


Fig. 6.— The ionization temperature vs. the electron temperature for various MM SNRs (red open square) and Shell-like SNRs (blue open circle). The dashed-line represents $kT_e = kT_z$, implying that the plasma is at the CIE state.

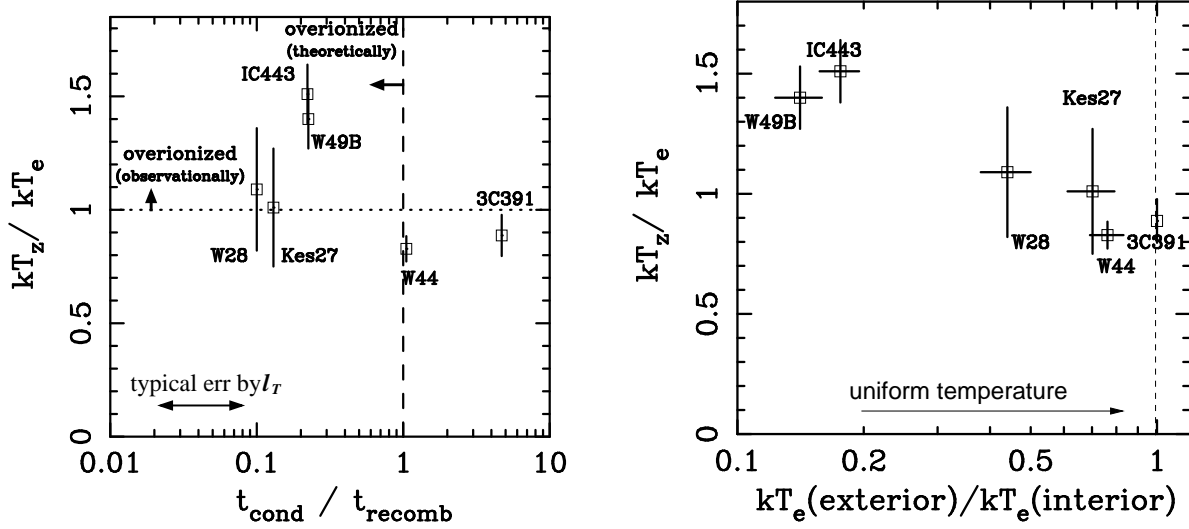


Fig. 7.— Comparisons between overionized SNRs and the other MM SNRs. *left*: The relations of the ionization states (kT_z/kT_e) to the timescale ratio ($t_{\text{cond}}/t_{\text{recomb}}$) for the MM SNRs. The typical error of the ratio due to uncertainties in l_T is also shown at the lower left of the panel. The condition $t_{\text{cond}}/t_{\text{recomb}} > 1$ means that it is hard for the plasma to be overionized due to thermal conduction. *right*: The relations of the ionization states (kT_z/kT_e) to the electron temperature gradients ($kT_e(\text{exterior})/kT_e(\text{interior})$) for the MM SNRs. The dashed line denotes $kT_e(\text{exterior})/kT_e(\text{interior}) = 1$, meaning a uniform temperature within the remnant. For 3C391 with no detection of temperature difference within the remnant, we assumed the uniform temperature.

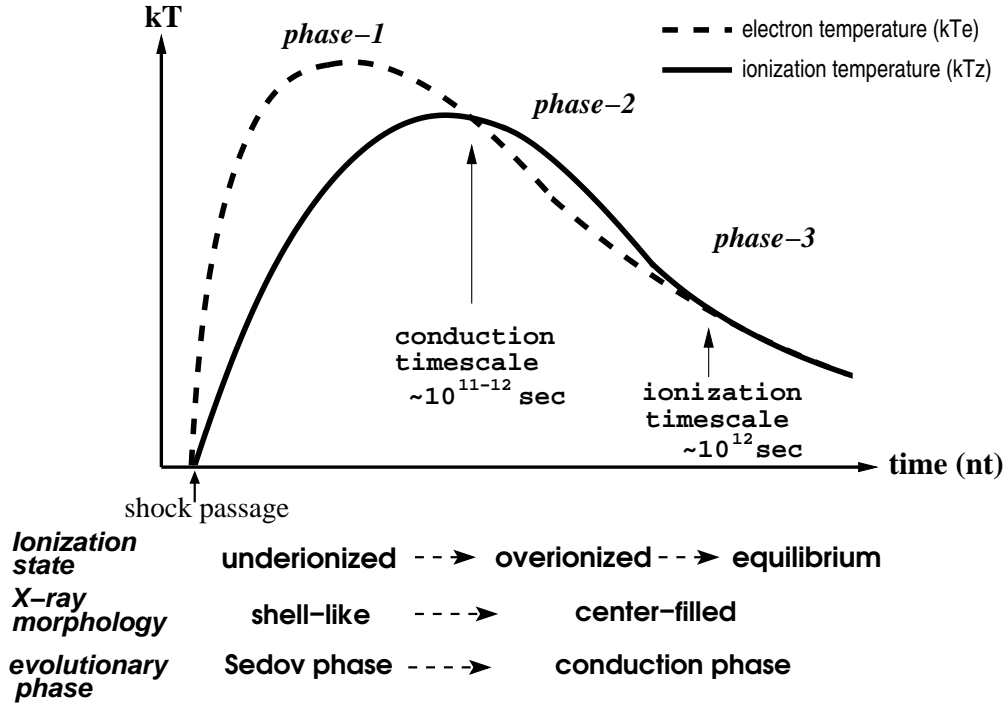


Fig. 8.— Schematic view of the evolution of the ionization state in an SNR along time. The horizontal line indicates the time normalized by the plasma density, and the vertical line qualitatively shows the electron and ionization temperatures. The ionization temperature follows the electron temperature with a delay of $n_e t \sim 10^{12} \text{ s cm}^{-3}$.

Table 1. The list of MM SNR candidates with *ASCA* observation logs

SNR name	Size (arcmin)	Group ^a	<i>ASCA</i> Obs.	Exposure time ^b
W28	42	A	1994/4, 1995/9	50ks(1994/4, 4CCD)
W44	28×34	A	1994/4, 10	24ks(1994/4), 26ks(1994/10)
3C400.2	28	A	1994/10 ^c , 1996/4	
Kes 27	20	A	1994/8	23ks
MSH 11-61A	12	A	1994/3 ^d , 1995/1	
3C391	8	A	1994/4	44ks
CTB 1	34	A	1996/1	
W51C	25×19	B	1995/10	
CTA 1 ^e	80	B	1996/1, 1997/2	
W63	95×65	B	1997/6	
HB21	120×90	B	1997/6	
IC 443	50	C	1993/4, 1994/3, 1998/3, 1999/3	72ks(1993/4)
Kes 79	11	C	1995/4	
HB3	70	C	1996/8	
G327.1–1.1 ^e	14	D	1996/3	
CTB 104A	80	D	no observation	
W49B	3.5	E	1993/4, 5, 10, 11	46ks(1993/4)
3C 397	6	E	1995/4	
MSH 11-54	10	F	1993/8	

^aclassification of the MM SNR candidates assigned by Rho & Petre (1998): The group A remnants are the prototypical MM SNRs, group B remnants are probably MM SNRs, and group C remnants show additional spatial components. Group D remnants are those whose data quality are too poor to allow any determination. Group E are probably not MM SNRs; nevertheless, they have similar characteristics, and so their classification remains uncertain. Group F is definitely not an MM SNR.

^bEffective SIS (SIS0 + SIS1) exposure time after screening are listed for the targets that we analyzed in this paper.

^cThe target was out of the field of view because of a pointing error

^dDue to observation at small Earth angle, only a small fraction of the SIS data remains after the screening (Slane et al. 2002).

^e*ASCA* observations revealed the non-thermal component that suggests these remnants are a true composite type (Slane et al. 1997; Sun, Wang, & Chen 1999).

Table 2. The best-fit parameters of the two CIE model for the W49B spectra

parameter (unit)		value	(90% c.r.)
wabs ^a	N_{H} (10^{22}cm^{-2})	5.23	(5.13–5.34)
Low-T plasma	kT_{e} (keV)	0.24	(0.22–0.28)
	E.M. ^b	2.7	(1.0–5.8)
High-T plasma	kT_{e} (keV)	1.70	(1.66–1.72)
	E.M. ^b	0.094	(0.090–0.097)
Abundance	Mg	0.55	(0.18–0.92)
	Al	0	(<1.74)
	Si	3.5	(3.2–3.8)
	S	3.9	(3.7–4.3)
	Ar	3.2	(2.8–3.7)
	Ca	4.5	(4.0–5.1)
	Fe	5.5	(4.9–6.2)
	Ni	16	(7.4–25)
Ar XVIII $K\alpha$	flux ^c	7.5	(4.4–10.7)
Ca XX $K\beta$	flux ^c	5.2	(3.4–7.1)
Cr XXIII $K\alpha$	flux ^c	2.0	(0.7–3.4)
Mn XXIV $K\alpha$	flux ^c	1.0	(<1.6)
$\chi^2/\text{d.o.f.}$		233/146	

Note. — Each abundance is relative to the solar value and those of two plasma components are linked together. The 90% confidence range (c.r.) for temperature, abundances, and line parameters are given in brackets. The line width of each Gaussian profile is fixed to 0.

^aThe column density of an interstellar absorption assuming solar abundances.

^bEmission Measure: the unit is $4\pi d^2 \times 10^{14} \text{ cm}^{-5}$ where d is the distance to W49B.

^cThe unit is $10^{-5} \text{ photons cm}^{-2} \text{ s}^{-1}$.

Table 3. The best-fit parameters for the W44 spectra

parameter(unit)	Center	North
	value (90% c.r.)	value (90% c.r.)
N_{H} (10^{22}cm^{-2})	0.89 (0.84–1.04)	1.03 (0.90–1.25)
kT_{e} (keV)	0.84 (0.79–0.86)	0.64 (0.59–0.68)
n_{et} ($10^{12}\text{ cm}^{-3}\text{ s}$)	10 (>1.1)	9.5 (>1.0)
E.M. ^a	6.1 (5.4–7.8)	10.5 (8.4–13.5)
Abundance		
Ne	0.60 (0.16–0.82)	0.33 (0.16–0.58)
Mg	0.78 (0.51–0.89)	0.21 (0.13–0.30)
Si	1.18 (0.96–1.32)	0.50 (0.46–0.60)
S	0.82 (0.61–1.01)	0.50 (0.33–0.65)
Fe	0 (<0.04)	0.02 (<0.10)
Ni	0 (<0.2)	0 (<0.4)
$\chi^2/\text{d.o.f.}$	91/87	83/83

Note. — Each abundance is relative to the solar value. The 90% confidence range (c.r.) for temperature, ionization timescale, and abundances are given in brackets.

^aEmission Measure: the unit is $4\pi d^2 \times 10^{12}\text{ cm}^{-5}$ where d is the distance to W44.

Table 4. The best-fit parameters for the W28 spectra

parameter(unit)	Center	East
	value (90% c.r.)	value (90% c.r.)
N_{H}^{a} (10^{21}cm^{-2})	5.1 (4.9–5.9)	5.4 (5.1–6.1)
Low-T plasma (VNEI)		
kT (keV)	0.62 (0.59–0.65)	0.61 (0.60–0.63)
$n_{\text{e}}t$ ($10^{12}\text{ cm}^{-3}\text{ s}$)	31 (>2.7)	15 (>1.0)
E.M. ^b	1.7 (1.2–2.2)	0.9 (0.8–1.1)
High-T plasma (VNEI)		
kT (keV)	1.41 (1.31–1.67)	1.37 (1.31–1.49)
$n_{\text{e}}t$ ($10^{12}\text{ cm}^{-3}\text{ s}$)	0.5 (0.3–2.1)	0.4 (0.3–0.8)
E.M. ratio ^c	0.51 (0.32–0.74)	0.31 (0.27–0.37)
Abundance		
Ne	0.28 (<0.88)	0 (<0.52)
Mg	0.94 (0.65–1.29)	1.17 (1.04–1.58)
Si	0.50 (0.37–0.58)	0.65 (0.55–0.77)
S	0.10 (<0.29)	0.54 (0.30–0.83)
Fe	0.53 (0.48–0.58)	0.62 (0.56–0.79)
$\chi^2/\text{d.o.f.}$	137/129	162/180

Note. — Each abundance is relative to the solar value and those of two plasma components were linked together. The 90% confidence range (c.r.) for temperature, ionization timescale, and abundances are given in brackets.

^aThe column density of an interstellar absorption assuming solar abundances.

^bEmission Measure: the unit is $4\pi d^2 \times 10^{12}\text{ cm}^{-5}$ where d is the distance to W28.

^cThis factor represents the ratio of the high-T emission measure to the low-T one.

Table 5. The best-fit parameters for the 3C 391 spectrum

Parameter [unit]	Entire region (90% c.r.)
N_{H} [10^{22} cm $^{-2}$]	2.99 (2.89–3.10)
kT_{e} [keV]	0.53 (0.50–0.57)
$n_{\text{e}}t$ [10^{12} cm $^{-3}$ s]	2.5 (> 0.9)
Mg	1.24 (1.03–1.48)
Si	1.12 (0.98–1.26)
S	0.81 (0.56–1.07)
E.M. [¶]	14.4 (11.9–17.8)
$\chi^2/\text{d.o.f}$	93/83

Note. — Each abundance is relative to the solar value. The 90% confidence range (c.r.) are given in brackets.

[¶]Emission Measure: the unit is $4\pi d^2 \times 10^{12}$ cm $^{-5}$ where d is the distance to 3C391.

Table 6. The best-fit parameters for the Kes 27 spectrum

Parameter [unit]	Entire region (90% c.r.)
N_{H} [10^{22} cm $^{-2}$]	2.2 (2.0–2.3)
kT_{e} [keV]	0.94 (0.84–1.01)
$n_{\text{e}}t$ [10^{12} cm $^{-3}$ s]	0.7 (> 0.3)
Mg	1.0 (0.6–1.8)
Si	1.4 (1.3–2.0)
S	1.2 (0.8–1.6)
E.M. [¶]	3.09 (2.52–3.40)
$\chi^2/\text{d.o.f}$	64/64

Note. — Each abundance is relative to the solar value. The 90% confidence range (c.r.) are given in brackets.

[¶]Emission Measure: the unit is $4\pi d^2 \times 10^{12}$ cm $^{-5}$ where d is the distance to Kes 27.

Table 7. Electron temperatures and densities of mixed-morphology SNRs and Cygnus Loop

SNR	region	electron temperature [keV]	density [cm ⁻³]
IC 443	interior	1.08 ± 0.03	1.0
	exterior	0.19 ± 0.02	4.2
W49B	interior	$1.70^{+0.02}_{-0.04}$	2.5
	exterior	$0.24^{+0.04}_{-0.02}$	18
W28	center, southwest	$1.41^{+0.25}_{-0.10}$	$0.25^{(1)}$
	center, northeast	0.62 ± 0.03	$0.75^{(1)}$
W44	center	$0.84^{+0.02}_{-0.05}$	$0.4^{(2)} \dagger$
	north	$0.64^{+0.04}_{-0.05}$	-
3C391	entire	$0.53^{+0.04}_{-0.03}$	1.1
Kes 27	center	$0.84 \pm 0.08^{(3)}$	0.16^\dagger
	rim	$0.59^{+0.04(3)}_{-0.06}$	-
Cygnus Loop	center	$0.82^{+0.09(4)}_{-0.07}$	-
	northeast limb	$0.22\text{--}0.30^{(5)}$	-

[†]mean density of the entire remnant.

References. — (1)Rho & Borkowski (2002); (2)Harrus et al. (1997); (3)Enoguchi et al. (2002); (4)Miyata et al. (1998); (5)Miyata et al. (1994).

Table 8. Electron and ionization temperatures of mixed-morphology SNRs

SNR name	(region)	kT_e [keV]	kT_z [keV]	Element ^b
IC 443 ^a	(center)	$0.99^{+0.04}_{-0.05}$	$1.49^{+0.09}_{-0.10}$	S
W49B ^a	(entire)	$1.77^{+0.04}_{-0.03}$	$2.47^{+0.21}_{-0.20}$	Ca
W28 ^a	(east)	$1.07^{+0.43}_{-0.28}$	$0.93^{+0.33}_{-0.31}$	Si
W44	(center)	$0.78^{+0.03}_{-0.04}$	$0.68^{+0.05}_{-0.04}$	Si
3C391	(entire)	$0.53^{+0.03}_{-0.04}$	$0.47^{+0.03}_{-0.05}$	Mg
Kes 27	(entire)	$0.82^{+0.19}_{-0.16}$	$0.83^{+0.11}_{-0.12}$	Si

^aDerived temperatures are for the high-temperature plasma.

^bThis column shows elements used to estimate the ionization temperature of the plasma.

Table 9. Electron and ionization temperatures of shell-like SNRs

SNR name	kT_e [keV]	$\log(n_e t)$ [s cm ⁻³]	kT_z [keV]	Element	reference
Cassiopeia A	$3.02^{+0.30}_{-0.24}$	$10.83^{+0.02}_{-0.04}$	$1.07^{+0.02}_{-0.04}$	S	our work
Kepler’s SNR	2.38 ± 0.14	10.84 ± 0.03	0.97 ± 0.03	S	1
Tycho’s SNR ^a	0.85 ± 0.15	11.0 ± 0.1	0.57 ± 0.03	Si	2
G352.7–0.1	$2.0^{+1.6}_{-0.7}$	$11.0^{+0.5}_{-0.3}$	$1.00^{+0.46}_{-0.22}$	S	3
Puppis A	0.72 ± 0.06	10.47 ± 0.07	$0.353^{+0.011}_{-0.008}$	Mg	4
RCW 86	$0.430^{+0.015}_{-0.017}$	10.71 ± 0.05	$0.286^{+0.005}_{-0.004}$	Mg	5
Cygnus Loop ^b	$0.82^{+0.09}_{-0.07}$	$10.35^{+0.06}_{-0.07}$	$0.54^{+0.05}_{-0.06}$	Si	6

References. — (1)Kinugasa & Tsunemi (1999); (2)Hwang & Gotthelf (1997); (3)Kinugasa et al. (1998); (4)Tamura (1994); (5)Rho et al. (2002); (6)Miyata et al. (1998).

^aFor Tycho’s SNR, both kT_e and $n_e t$ are derived from Si and S line diagnostics, not from NEI model fittings. Details are described in Hwang & Gotthelf (1997).

^bisted kT_e and $n_e t$ are those in the central region of the remnant, see Miyata et al. (1998).